Direct Imaging of Exoplanets: Science and Techniques
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Suppressing Speckle Noise for Simultaneous Differential Extrasolar Planet Imaging (SDI) at the VLT and MMT

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Abstract.
We discuss the instrumental and data reduction techniques used to suppress speckle noise with the Simultaneous Differential Imager (SDI) implemented at the VLT and the MMT. SDI uses a double Wollaston prism and a quad filter to take 4 identical images simultaneously at 3 wavelengths surrounding the 1.62 μm methane bandhead found in the spectrum of cool brown dwarfs and gas giants. By performing a difference of images in these filters, speckle noise from the primary can be significantly attenuated, resulting in photon noise limited data past 0.5". Non-trivial data reduction tools are necessary to pipeline the simultaneous differential imaging. Here we discuss a custom algorithm implemented in IDL to perform this reduction. The script performs basic data reduction tasks but also precisely aligns images taken in each of the filters using a custom shift and subtract routine. In our survey of nearby young stars at the VLT and MMT (see Biller et al., this conference), we achieved H band contrasts >25000 (5σ ΔF1(1.575 μm) > 10.0 mag, ΔH>11.5 mag for a T6 spectral type object) at a separation of 0.5" from the primary star. We believe that our SDI images are among the highest contrast astronomical images ever made from ground or space for methane rich companions.

Keywords. instrumentation: adaptive optics, methods: data analysis, techniques: image processing, (stars:) planetary systems

1. Introduction

In theory, adaptive optics (AO) systems that are "photon noise limited" can detect an object up to 10^{5-6} times fainter its primary at separations of $\sim$1" – sufficient to detect a young, self-luminous giant extrasolar planet. However, overcoming the large contrast difference between star and planet is not the only obstacle in directly detecting extrasolar planets – all AO also systems suffer from a limiting "speckle noise" floor (Racine et al. 1999). Within 1" of the primary star, the field is filled with speckles left over from instrumental features and residual atmospheric turbulence after adaptive optics correction. These speckles vary as a function of time and color. For photon noise limited data, the signal to noise S/N increases as $t^{0.5}$, where t is the exposure time. For speckle-noise limited data, the S/N does not increase with time past a specific speckle-noise floor (limiting contrasts to $\sim 10^3$ at 0.5"). This speckle-noise floor is considerably above the photon noise limit and makes planet detection very difficult. Interestingly, space telescopes such as HST also suffer from a somewhat similar limiting speckle-noise floor due to imperfect optics and "breathing" (Schneider et al. 2003). Direct detection of

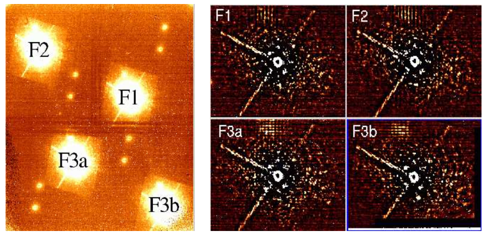

Figure 1. Left: Two minutes of raw SDI data from NACO SDI's 1024×1024 Aladdin array in the CONICA AO camera (Lenzen et al. 2004). Right: Same dataset, slightly processed. Apertures have been selected around each filter image. In order to reveal the speckle pattern, a heavily smoothed image was subtracted from the raw images (unsharp masking). The resulting speckle patterns are very similar between the 4 simultaneous images which means that an effective subtraction of speckles can be obtained between the filters.

extrasolar giant planets requires special instrumentation to suppress this speckle noise floor and produce photon noise limited images.

Simultaneous Differential Imaging is an instrumental method which can be used to calibrate and remove the "speckle noise" in AO images, while also isolating the planetary light from the starlight. This method was pioneered by Racine et al. (1999), Marois et al. (2000), Marois et al. (2002) and Marois et al. (2005). It exploits the fact that all cool (T_{eff} <1200 K) extra-solar giant planets are thought to have strong CH_4 (methane) absorption redwards of 1.62 μm in the H band infrared atmospheric window (Burrows et al. 2001, Burrows et al. 2003). Our SDI device obtains four images of a star simultaneously through three slightly different narrowband filters (sampling both inside and outside of the CH_4 features). These images are then differenced. This subtracts out the halo and speckles from the bright star to reveal any massive extrasolar planets orbiting that star. Since a massive planetary companion will be brightest in the F1(1.575 μm) filter and absorbed in the rest, while the star is bright in all three, a difference can be chosen which subtracts out the star's light and reveals the light from the companion. Thus, SDI also helps eliminate the large contrast difference between the star and substellar companions.

2. The SDI AO Cameras at the VLT and MMT

SDI optics are currently implemented at the 6.5m MMT (using the MMT AO adaptive secondary mirror and the ARIES AO camera – McCarthy et al. 1998) and at the ESO VLT (using the 8m UT4 and the NAOS-CONICA (NACO) AO system) by a group headed by L. Close and R. Lenzen (Close et al. 2005, Lenzen et al. 2004, Lenzen et al. 2005). Both devices are fully commissioned and available for observing.

The SDI technique requires some specialized optics consisting of a cryogenic custom double calcite Wollaston device and a focal plane quad CH_4 filter. Our custom Wollaston splits the beam into four identical beams while minimizing non-common path errors. The *differential* non-common path errors are less than 20 nm RMS per Zernike mode between the beams (Lenzen et al. 2004). Each of the four beams is fed through one of the filters on the quad filter. Filter wavelengths were chosen on and off the methane absorption feature at 1.62 μm and were spaced closely (every 0.025 μm) in order to limit residuals due to speckle and calcite chromatism. We used four filters F1, F2, F3a, and F3b with central wavelengths F1=1.575 μm, F2=1.600 μm, and F3a=F3b=1.625 μm. The filters are approximately 0.025 μm in bandwidth. A cold 5"×5" focal plane mask has been implemented as a field stop for the VLT device. No coronagraph is currently used, since

the Strehl ratios (∼20-30%) are too low to increase the contrasts significantly. The special f/40 SDI camera has a platescale of 0.017″/pix at the VLT and 0.02″/pix at the MMT.

The SDI device has already produced a number of important scientific results: the discovery of AB Dor C (Close et al. 2005) which is the tightest (0.16") low mass companion detected by direct imaging, detailed surface maps of Titan (Hartung et al. 2004), the discovery of ϵ Indi Ba-Bb, the nearest binary brown dwarf (McCaughrean et al. 2005), and evidence of orbital motion for Gl 86B, the first known white dwarf companion to an exoplanet host star (Mugrauer and Neuhäuser 2005).

3. Observational Technique and Data Reductions

A raw dataset from NACO SDI is shown in Fig. 1. The inner 0.2" diameter core is saturated in each image to increase signal in the halo. After unsharp masking, we find that the speckle patterns in each of the separate filters are nearly identical. (See Fig. 1). This bodes well for our ability to attenuate speckle noise.

To distinguish between faint planets and any residual speckles, we observe each object at a variety of position angles (usually a series of 0° and 33° observations). Instrumental and telescope "super speckles" (Racine et al. 1999) should not rotate with a change of rotator angle; however, a real planet should appear to rotate by the change in rotator angle. The data is reduced using a custom IDL script. A pipeline block diagram for this IDL script is presented in Fig. 2. Alignments are performed using a custom shift and subtract algorithm. We calculate 2 differences (and one non-differenced combination) which are sensitive to substellar companions of spectral types "T" (T_{eff} < 1200 K), "Y" (T_{eff} ⩽ 600 K), and "L" (T_{eff} > 1200 K). Data taken at different position angles are subtracted (e.g. 20 minutes of data at 0 degrees minus 20 minutes of data at 33 degrees) in order to further attenuate speckle noise.

A fully reduced dataset from the VLT SDI device as well as the same dataset reduced in a standard AO manner is presented in Fig. 3. Simulated planets were inserted into the dataset pre-reduction. In the SDI reduction, simulated planets with ΔF1=10 (attenuation in magnitudes in the 1.575 μm F1 filter) are detected with S/N > 10 past 0.7". In comparison, none of the simulated planets are clearly detected in the standard AO data reduction and numerous bright super speckles remain in the field. A plot of ΔF1 (for 5σ detections) vs. separation from the primary is presented in Fig. 3. For this dataset, we achieved star to planet H band contrasts (5σ) >25000 (5σ ΔF1(1.575 μm) > 10.0 mag, or ΔH>11.5 mag for a T6 spectral type object) at a separation of 0.5" from the primary star – approaching the photon-noise limit in 40 minutes of data. ΔF1(1.575 μm) and ΔH (for a methane object) for 3 of our survey stars (see Biller et al. this conference) as well as for two other comparison objects are shown in Table 1 – it is clear that the achievable contrast varies according to the magnitude of the object and total exposure time. We believe these are among the most sensitive astronomical images taken to date for methane rich companions.

Acknowledgements

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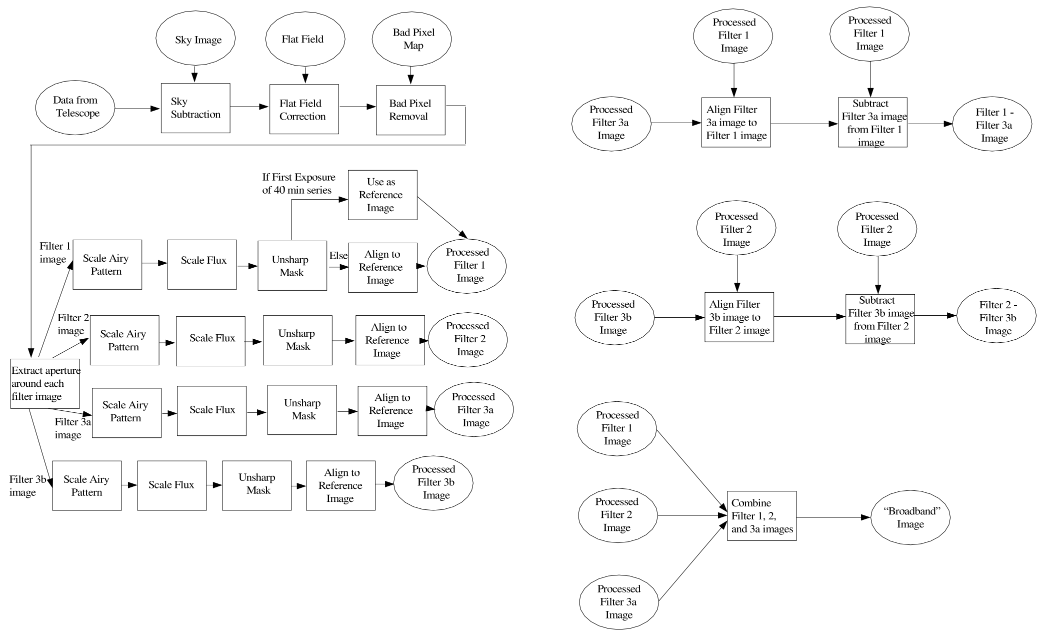

Figure 2. Pipeline Block Diagrams

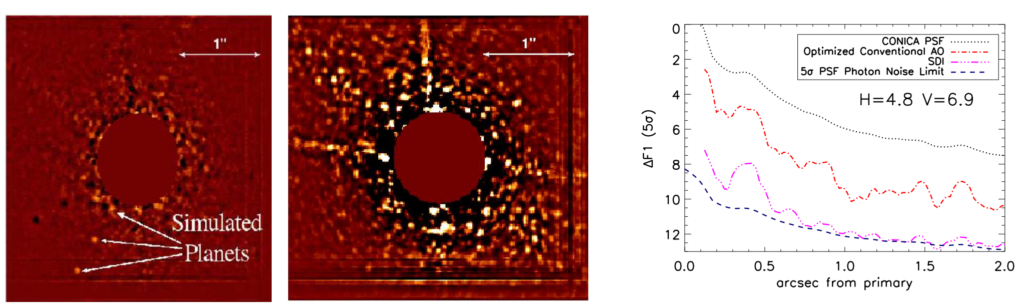

Figure 3. Left: A complete reduced dataset (40 minutes of data at a series of rotator angles – 0°, 33°, 33°, 0°) from the VLT SDI device. Simulated planets have been added at separations of 0.55, 0.85, and 1.35" from the primary, with ΔF1 = 10 mag (attenuation in magnitudes in the F1 1.575 μm filter) fainter than the primary. These planets are scaled from unsaturated images of the example star taken right before the example dataset (and have fluxes in each filter appropriate for a T6 object). Past 0.7", the simulated planets are detected with S/N > 10. **Center:** Standard AO data reduction of the same dataset. Images have been coadded, flat-fielded, sky-subtracted, and unsharp-masked. Simulated planets have been added with the same properties and at the same separations as before. None of the simulated planets are clearly detected in the standard AO reduction. Additionally, numerous bright super speckles remain in the field. **Right:** ΔF1 (5σ noise level in the 1.575 μm F1 filter) vs. Separation for 40 minutes of VLT SDI data for a 70 Myr K1V star at 15 pc. The top curve is the AO PSF. The next curve is the "classical AO PSF" unsharp masked. The third curve down is 40 minutes of SDI 0°-33° data. The last curve is the theoretical contrast limit due to photon-noise. At star-companion separations > 0.5", we are photon-noise limited and achieve star to planet H band contrasts $>$25000 (5σ ΔF1(1.575 μm) > 10.0 mag, ΔH$>$11.5 mag for a T6 spectral type object) at a separation of 0.5" from the primary star.

Table 1. Properties of Example SDI Survey Stars and Comparison Stars

Case	Spectral Type	Age	Distance	H	V	Exposure Time	ΔF1[1]	ΔH[1]
A	K2V	30 Myr	45.5 pc	7.1	9.1	40 min	10.5	12
B	K1V	70 Myr	15 pc	4.8	6.9	40 min	10.5	12
C	M3V	30 Myr	24 pc	7.1	12.2	40 min	10	11.5
10 late K-M stars[2]	K-M	0-1 Gyr	10-50 pc	6.4-8.7	8-12	10-25 min	8.61	10.31
Gl 86[3]	K1V	10 Gyr	10.9 pc	4.2	6.2	80 min	12.8	14.3

[1] 5σ at 0.5" [2] Masciadri et al. IAUC 200 [3] Mugrauer & Neuhäuser 2005

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